CALIBRATION OF AN INSTRUMENTED SURGICAL FORCEPS USING BOOTSTRAP TECHNIQUE: A COMPARATIVE STUDY

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INTRODUCTION

Knowledge of forces, exerted on the brain tissue during the performance of neurosurgical tasks, is critical for quality assurance, case rehearsal, and training purposes. Novice surgeons and neurosurgery residents are taught about this force through either hands-on training in the operating room and model-based practice while supervised by mentors [1], or surgical training tools such as virtual reality simulators [2]. Conventional training requires supervision of an expert surgeon and is time consuming. Neurosurgical simulators or surgical training models cannot precisely reflect the clinical situation as they utilize mechanical models obtained through simulation techniques, other than experimental data. Hence, there is an increasing demand to provide quantitative evaluation of surgical performance using quantitative measures such as tool-tissue interaction forces [3, 4].

Developing *SmartForceps*, a bipolar forceps retrofitted by a set of strain gauges, has helped to quantify the interaction forces using voltages read from strain gauges mounted on both prongs of the tool [5, 6]. Each cell of a strain gauge is based on an elastic element to which a number of electrical resistances are bonded [7]. When an external force is applied to the rigid body (e.g., a bipolar forceps) to which the strain gauge is attached, the elastic elements are deflected and a voltage is produced due to changes in the resistance [8]. Thus, there is a relationship between the external force (explanatory variable) and the read voltage (response variable) that should be quantified to estimate the force.

Recently, a methodology based on the deterministic and physical properties of the force-sensing strain gauges is developed to obtain estimates of the force using the observed voltages [8]. This technique, which is called the *Naïve* method hereafter, does not allow to obtain the precision associated with each estimate and construct necessary confidence intervals. The proposed method in [8] does not properly use the information of the training data set to fit the calibration model required for estimating the force and studying statistical properties of the estimates. In addition, it assumes the same distribution for the voltages in the calibration stage and the real surgery in order to perform necessary estimation steps [8].

In this paper, we employ a linear regression methodology and use a Bootstrap approach to obtain both point and interval estimates of the applied forces at the tool tips. We use a nonparametric Bootstrap approach that does not require the normality assumption about the distribution of produced voltages and provide the precision associated with each estimate. Compared to the method employed in [8], the proposed methodology incorporates the effect of each surgeon using the forceps in the estimation process through a pooling stage required in the procedure.

CALIBRATION STATION

Configuration of the force-sensing strain gauges on the medical bipolar forceps is illustrated in Figure (a). Each strain-gauge was connected to a set of precise resistors to form a Wheatstone bridge configuration. The principle of a wire strain gauge is based on changes in the resistance of a wire, and is correlated to changes in strain (deflection in the wire) [8]. Figure 1 (b) shows the automatic calibration station developed for force calibration of the bipolar forceps. The station consisted of a titanium Nano17 force/torque sensor (ATI Industrial Automation, North Carolina, USA) that was connected to a signal conditioning box (ATI DAQ F/T, ATI Industrial Automation North Carolina, USA) and a NI USB-6251 data acquisition board (National Instruments, Texas, USA).

The force sensor was mounted on a motorized platform controlled with a push button or can be controlled automatically by a motor controller and a real-time control software in Simulink and Matlab. The control signal was sent to an analog output of a data acquisition board (Q2-USB, Quanser consulting Inc. Markham, Ontario, Canada). The bipolar forceps was secured on several mounts, each with a different orientation in order to individually test/calibrate each force. To calibrate along each axis, the force sensor was advanced in small incremental steps. Therefore, output from the Nano17 Titanium force sensor (ATI Six-Axis force/torque sensor, ATI Industrial Automation, Apex, NC, USA) and corresponding voltages of the strain gauges were recorded to obtain their relationship.

BOOTSTRAP TECHNIQUE

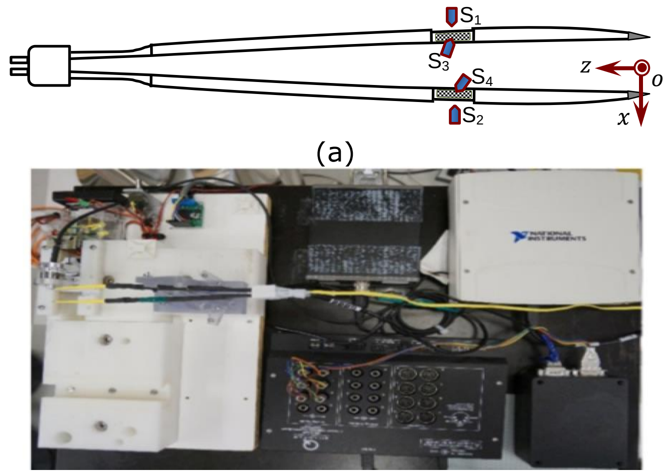
Detailed explanation of the Bootstrap technique, its applications and examples are presented in [9]. In this application, for each force component, F_x or F_y, there are voltages, each produced by a strain gauge. After fitting proper models, the interest lies in estimating the unknown values of forces associated with observed values of voltages in a strain gauge.

To implement the Bootstrap technique, we used both the training and unknown data sets. The training data set was obtained under a control setting that covers the required range of the forces. However, for the Unknowns, we only observed the voltages and the goal was to estimate their associated forces.

First, we fit the following models to the training data sets:

$$\begin{pmatrix} V_{x1} \\ V_{y1} \end{pmatrix} = (\alpha_1 \quad \beta_1)\begin{pmatrix} F_x & 0 \\ 0 & F_y \end{pmatrix} + \begin{pmatrix} \varepsilon_{x1} \\ \varepsilon_{y1} \end{pmatrix}, \quad (1)$$

$$\begin{pmatrix} V_{x2} \\ V_{y2} \end{pmatrix} = (\alpha_2 \quad \beta_2)\begin{pmatrix} F_x & 0 \\ 0 & F_y \end{pmatrix} + \begin{pmatrix} \varepsilon_{x2} \\ \varepsilon_{y2} \end{pmatrix}, \quad (2)$$



(a)

(b)

Figure 1: (a) Configuration of strain gauges on prongs of the bipolar forceps, (b) Station designed to calibrate the bipolar forceps.

where, (V_{x1}, V_{x2}) and (V_{y1}, V_{y2}) are the observed voltages when the surgeon applies the forces F_x and F_y, respectively. The error is represented by $\varepsilon_{x1}, \varepsilon_{x2}, \varepsilon_{y1}$ and ε_{y2}. In order to construct the Bootstrap data set, required for calibration, residuals are obtained from both training and unknowns to form the residual pool. This will incorporate effects of the surgeon's surgical skill and rhythm of surgery through combining data from the calibration station and the real operation.

Due to low variation of the residuals, they are adjusted by an adjusting factor, $\sqrt{n/(n-p)}$, where n is the number of data points and p is the number of parameters [10].

After fitting the necessary regression models, the following steps are used in order to obtain Bootstrap estimates of the forces F_x and F_y:

1) Calculate $\widehat{\alpha_1}$, $\widehat{\beta_1}$, and $\widehat{\alpha_2}$, $\widehat{\beta_2}$, from (2) and (3) using the training data set.
2) Calculate residuals using bellow equations for $i = 1,2,\ldots,n$:

$$\begin{pmatrix} \varepsilon_{x1i} \\ \varepsilon_{y1i} \end{pmatrix} = \begin{pmatrix} V_{x1i} \\ V_{y1i} \end{pmatrix} - (\widehat{\alpha_1} \quad \widehat{\beta_1})\begin{pmatrix} F_{xi} & 0 \\ 0 & F_{yi} \end{pmatrix}, \quad (4)$$

$$\begin{pmatrix} \varepsilon_{x2i} \\ \varepsilon_{y2i} \end{pmatrix} = \begin{pmatrix} V_{x2i} \\ V_{y2i} \end{pmatrix} - (\widehat{\alpha_2} \quad \widehat{\beta_2})\begin{pmatrix} F_{xi} & 0 \\ 0 & F_{yi} \end{pmatrix}. \quad (5)$$

3) Construct the Bootstrap data set, by resampling from residual pool to obtain:
Training:

$$\begin{cases} \begin{pmatrix} V^*_{x1i} \\ V^*_{y1i} \end{pmatrix} = (\widehat{\alpha_1} \quad \widehat{\beta_1}) \begin{pmatrix} F_{xi} & 0 \\ 0 & F_{yi} \end{pmatrix} + \begin{pmatrix} \varepsilon^*{}_{x1i} \\ \varepsilon^*{}_{y1i} \end{pmatrix}, \\ \begin{pmatrix} V^*_{x2i} \\ V^*_{y2i} \end{pmatrix} = (\widehat{\alpha_2} \quad \widehat{\beta_2}) \begin{pmatrix} F_{xi} & 0 \\ 0 & F_{yi} \end{pmatrix} + \begin{pmatrix} \varepsilon^*{}_{x2i} \\ \varepsilon^*{}_{y2i} \end{pmatrix}, \end{cases} \quad (6)$$

$$Unknown: \begin{cases} V^*_{0j1} = V_{0j1} + \varepsilon^*_{01j}, \\ V^*_{0j2} = V_{0j2} + \varepsilon^*_{02j}, \end{cases}$$

where ε^*_i is the random sample with replacement from the residual pool and (V_{0j1}, V_{0j2}) is the observed voltages.

4) Estimate $\widehat{\alpha_1^*}$, $\widehat{\beta_1^*}$, and $\widehat{\alpha_2}^*$, $\widehat{\beta_2}^*$, from (6) and Obtain $\hat{F_x}$ and $\hat{F_y}$ using:

$$\begin{cases} V^*_{0j1} = (\widehat{\alpha_1^*} \quad \widehat{\beta_1}^*) \begin{pmatrix} \widehat{F_{xi}} & 0 \\ 0 & \widehat{F_{yi}} \end{pmatrix}, \\ V^*_{0j2} = (\widehat{\alpha_2^*} \quad \widehat{\beta_2}^*) \begin{pmatrix} \widehat{F_{xi}} & 0 \\ 0 & \widehat{F_{yi}} \end{pmatrix}. \end{cases} \quad (7)$$

5) Start from 3 and repeat B times.

In order to obtain the data set for Training, the data from 20 trial runs were used during calibration of the bipolar forceps measured using the developed automatic calibration station, shown in Figure 1 (b). The motor, connected to the force sensor on the calibration station, was programmed to move in two directions: forward, *i.e.,* moving towards the point o in Figure 1 (a) and backward (moving away from the point *o*). Data measurement was performed for 10 times under the same test conditions along each direction. Therefore, in total, 40 sets of data were collected when the force was applied along *x* and *y*-axes (20 trial runs for forward and 20 trials for backward, for right prong. In forward motion, the tips were applied a force of 0 N to 2 N, and in backward, the force reduced from 2 N to 0 N. Note that the force of 2 N is the peak force that we can expect during the performance of neurosurgery [8].

From Tables 1 and 2, the length of force intervals obtained for the right tip in forward direction are narrower than the backward direction. For instance, when F_x is equal to 1 N, the force interval in forward direction for the right tip is (0.972 N, 1.019 N), while, in backward is (0.990 N, 1.043 N). Figure 2 illustrates the bounds for both forward and backward directions when F_x varies between 0 N and 1 N.

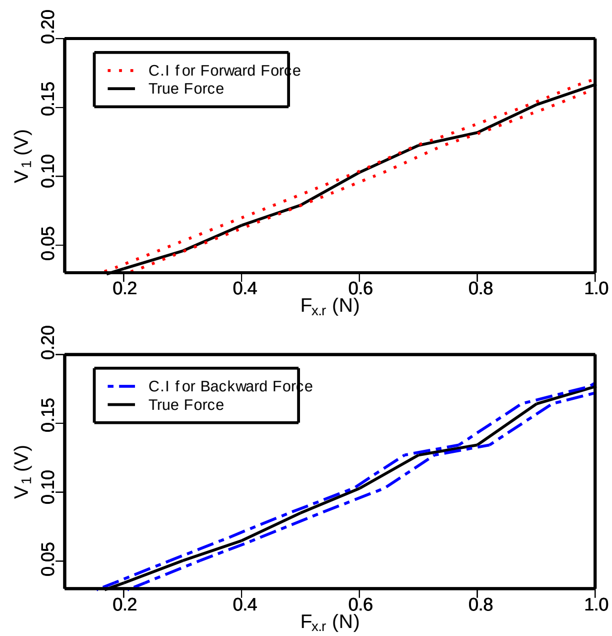


Figure 2: Bootstrap confidence intervals of the forces along *x*-axis, at the right tip in forward (top) and backward (bottom) directions.

Table 1: Estimated confidence interval for different F_x values applied to the right forceps.

Forces Applied to right Tip			
Forward Force		***Backward Force***	
True F_x	***C.I***	***True F_x***	***C.I***
0.1	(0.095, 0.139)	1.0	(0.990, 1.043)
0.2	(0.181, 0.227)	0.9	(0.875, 0.927)
0.3	(0.258, 0.303)	0.8	(0.769, 0.821)
0.4	(0.367, 0.413)	0.7	(0.676, 0.727)
0.5	(0.455, 0.502)	0.6	(0.544, 0.642)
0.6	(0.595, 0.641)	0.5	(0.481, 0.534)
0.7	(0.697, 0.742)	0.4	(0.364, 0.418)
0.8	(0.760, 0.807)	0.3	(0.279, 0.330)
0.9	(0.888, 0.932)	0.2	(0.184, 0.236)
1.0	(0.972, 1.019)	0.1	(0.093, 0.146)

Table 2: Estimated confidence interval for different F_y values applied to the right forceps.

Forces Applied to right Tip			
Forward Force		***Backward Force***	
True F_y	***C.I***	***True F_y***	***C.I***
0.1	(0.096, 0.192)	1.0	(0.933 ,1.047)
0.2	(0.179 ,0.277)	0.9	(0.832 ,0.943)
0.3	(0.252 ,0.350)	0.8	(0.747 ,0.858)
0.4	(0.373 ,0.470)	0.7	(0.618 ,0.727)
0.5	(0.497 ,0.592)	0.6	(0.552 ,0.663)
0.6	(0.510 ,0.605)	0.5	(0.444 ,0.557)
0.7	(0.632 ,0.729)	0.4	(0.331 ,0.442)
0.8	(0.774 ,0.870)	0.3	(0.259 ,0.368)
0.9	(0.875 ,0.974)	0.2	(0.159 ,0.269)
1.0	(0.992 ,1.087)	0.1	(0.090 ,0.201)

IMPLEMENTATION IN REAL FIELD

We implemented the bootstrap approach in a real field application to predict the tool-tissue interaction forces. The operating room, surgeon workstation, and the SmartForceps are depicted in Figure 3. The study was performed with the approval from the Conjoint Health Research Ethics Board (CHREB) of the University of Calgary. Surgeons used a Leica Microscope (M525 0H4, Leica Microsystems GmbH, Germany) to illuminate and magnify the surgical site.

The neurosurgical tasks were conducted by an experienced surgeon (GS) as the primary surgeon, and one assistant surgeon. The same *SmartForceps* was used during the experiment. The microscope video recording of the entire procedure wascaptured with a Blu-ray recorder. The start and end times of each task were recorded to allow for cross-referencing. Here we only report results from one dissection task as proof of concept: coagulating galea.

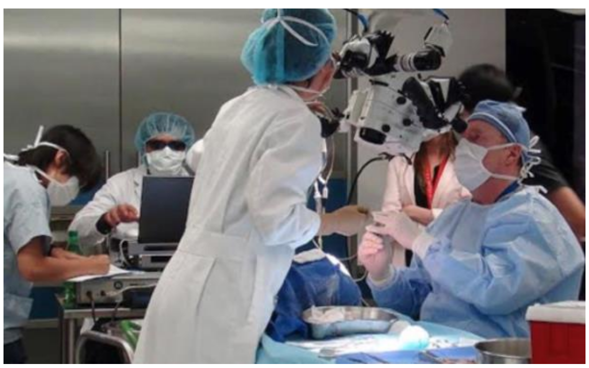


Figure 3: Workstation and experimental setup.

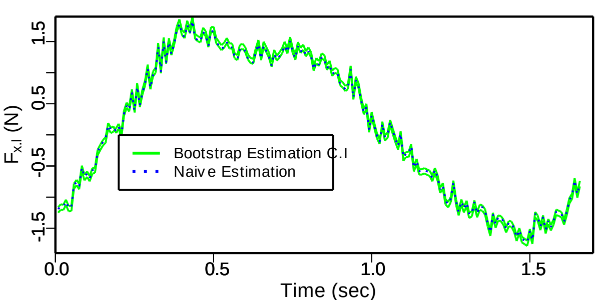


Figure 4: Results of estimating the interaction forces at the right tip (F_x) during the performance of coagulating galea task using both Naïve and Bootstrap techniques.

As observed in Figure 4, the interaction forces in both backward and forward directions were reported as confidence intervals along right tip. Figure 4also depicts the forces calculated using the Naïve method that was employed by the authors in [8]. As seen in Figure 4, the estimation based on the Naïve method are always within the estimated bounds obtained with the Bootstrap method.

CONCLUSIONS

In this paper, the Bootstrap technique was used to calibrate the interaction forces between a surgical tool (SmartForceps) and the brain tissue. We incorporated effects of the surgeon in the estimation process through a pooling stage in the procedure. Results indicated that the Bootstrap technique provides an accurate estimate of the force value, while providing the precision of performing a surgical task.

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